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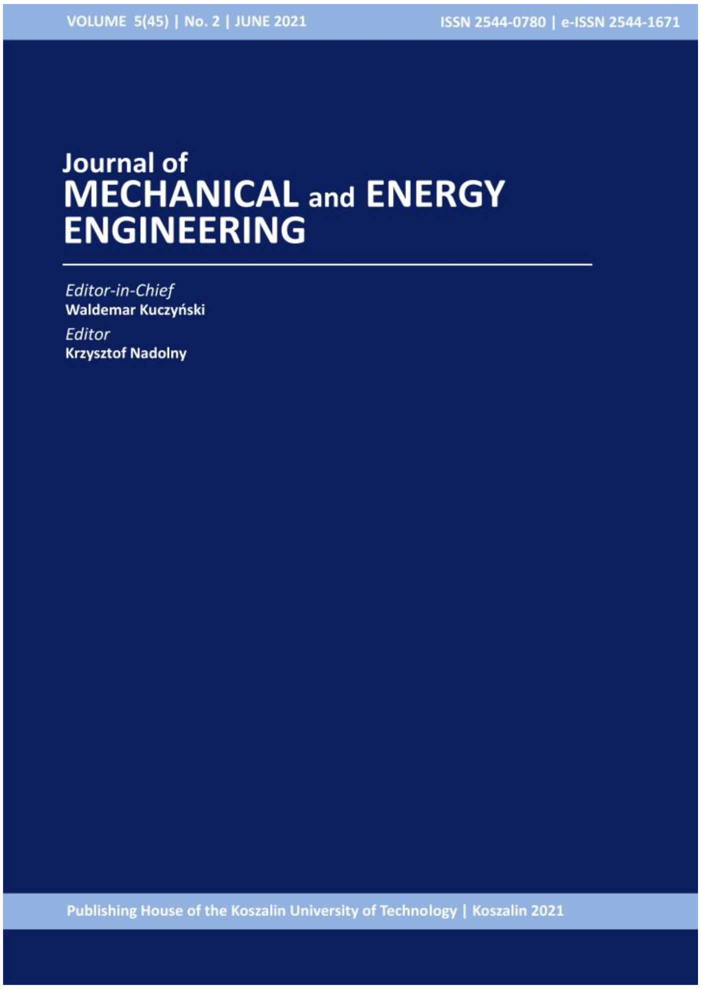

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# NUMERICAL ANALYSIS OF THE V-DIE BENDING PROCESS OF THE ZINC COATED DC01 STEEL

Mateusz MIKSZA[1*], Łukasz BOHDAL[2], Katarzyna KOŚKA[3]

[1*] Doctoral School of the Koszalin University of Technology, Sniadeckich 2, 75-453, Koszalin, Poland,
e-mail: mateusz.miksza@s.tu.koszalin.pl, https://orcid.org/0000-0002-4215-2665,
[2] Faculty of Mechanical Engineering, Department of Mechanics and Construction, Koszalin University of Technology, Raclawicka 15-17, 75-620, Koszalin, Poland, https://orcid.org/0000-0002-8085-9530,
[3] Doctoral School of the Koszalin University of Technology, Sniadeckich 2, 75-453, Koszalin, Poland,
https://orcid.org/0000-0002-1765-8859

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**Abstract:** This paper presents an FEM analysis of the V-die bending process of a zinc plated DC01 steel. The article presents a new approach to the analysis of the coated sheets bending process as simulation studies are not commonly used in this field, and most investigations concern experimental analyses. The process is analyzed in terms of maximum plastic strain and the reaction force on the punch. An analysis of the spring-back phenomenon was conducted. This paper shows the model preparation process as well as the results achieved and their interpretation. It has been shown that the coating layer thickness affects the bending reaction force acting on the punch as well as the scale of the springback phenomenon. The magnitude of the maximum plastic strain is also affected by the coating thickness.

**Keywords:** V-die bending, spring-back, plastic working, FEM analysis, galvanized steel

## 1. INTRODUCTION AND LITERATURE SURVEY

Sheet metal bending is widely used in metal processing. It is used in many industries: from furniture industry, through important structural parts used in automotive or aviation industries.

Due to the specificity of sheet metal elements usage it is important to meet a number of conditions, including appropriate dimensional and shape quality.

The V-die bending process can be described as acting on the sheet metal with a hydraulic driven punch, which causes permanent plastic deformation in the material. The acting force presses the material into a V-shaped die. The process diagram is shown in Figure 1.

Figure 1 illustrates the springback phenomenon which is indispensable in the processes of plastic processing of metals. In the case of the bending process, this phenomenon occurs as a difference between the bend angle of the sheet under load and the actual angle, obtained after unloading (lifting the punch). The difference occurs due to the presence of reversible elastic stresses in the material and also due to the fact that there are different stress zones in the cross-section of the sheet thickness, where the zone of compressive stress (from the punch side), tensile stress (from the die side) and the neutral zone can be observed at the same time [6].

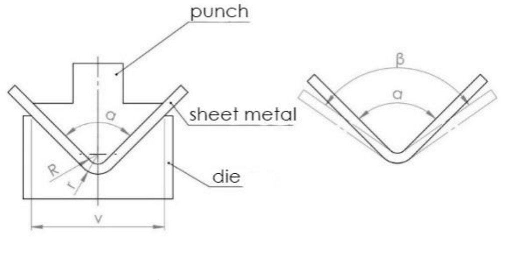

Fig. 1. Diagram of the bending process on V-type die: $R$ - punch radius, $r$ - die bottom radius, $v$ – die width, $\alpha$ - sheet bending angle under punch load, $\beta$ - actual sheet bending angle after releasing the load

In order to standardize the notation and to facilitate analyses, the dimensionless springback coefficient $K$ is commonly used. It is defined as:

$$K = \frac{\beta}{\alpha}, \tag{1}$$

where: $K$ – the springback coefficient, $\alpha$ – the sheet bending angle under the load, $\beta$ – the actual sheet bending angle after unloading [6].

The phenomenon of elastic springback is widely analysed due to the fact that it directly affects the dimensional and shape accuracy of parts manufactured. Its influence has to be considered in the production technology process.

Analytical methods of predicting the phenomenon of elastic recovery were presented in [3]. Comparison with the experimental results has proven their relatively high accuracy. Similar theoretical analyses were carried out in [11]; they were also compared with empirical tests. The authors of [1] proved that the springback angle is influenced by the sheet thickness and the bending radius: R. Increasing the bending radius intensifies the phenomenon, while increasing the sheet thickness reduces it. A different approach was presented in [2], where the springback prediction algorithm based on artificial neural networks was presented. As in publications [6] and [1], it was found that the main factors determining the value of the springback coefficient are the sheet thickness and the bend radius.

It is worth noting that the springback phenomenon is closely related with the strength properties of the material bent. A higher value of tensile strength and a lower value of Young's modulus increase the springback scale [6].

Article [13] shows that increasing the bending angle influences the springback coefficient value. It has been shown that increasing the bend angle increases the K coefficient. The influence of such factors as the sheet thickness and the bend radius was also confirmed. A numerical analysis of the bending process is yet another approach. The authors of [5] performed an FEM simulation of various thickness steel bending processes. It was confirmed that the value of the springback coefficient depends on the sheet thickness but it was demonstrated that after exceeding a certain critical value, further increase of sheet thickness again starts to have a negative effect.

Another numerical analysis was presented in [4]. Apart from confirming the influence of the sheet thickness and the punch radius on the springback angle, the bending forces were also analyzed. It was demonstrated that increasing the sheet thickness and the bend radius requires an application of a greater load. Additionally, residual plastic deformations were analyzed; the authors concluded that the total plastic strain on the tensile side of the sheet is greater than on the compression side. Similar conclusions regarding the influence of the bending radius and the sheet thickness were presented in [9], which were also based on numerical analyses using the finite element method.

The aforementioned sources focused on the uncoated metal bending process but it is a well-known fact that coated sheets are also widely used in the industry. One of the most popular materials used for anti-corrosive coatings on steel is zinc, although other metal coatings, such as nickel or chromium, are also commonly used.

The industrial grade galvanizing processes can be divided into galvanic processes, where the coating thickness ranges from $x$ = 1-20 μm [16], and hot-dip galvanizing processes, where the coating thickness can be much higher and it may exceed $x$ = 100 μm [18].

A partial analysis of the electrolytically coated sheets bending process is presented in [8]. Based on the CR4 steel bending process, it was shown that in the coating thickness range 0-10 μm, the springback coefficient value increases with the coating thickness increasing. Moreover, the article analyses the effect of the die width, and it was proved that the die with a wider groove increases the springback angle. Similar conclusions were presented in [7].

The paper [12] analyses the bending process of nickel-coated steel sheets with a coating thickness of 20 μm. Nickel coated sheets were proven to have a greater value of the springback coefficient. The authors claim this phenomenon is caused by a reduction of the friction coefficient between the sheet metal and the bending tools. In addition, the article analyses the effect of the sheet width and it shows that increasing it also increases the springback coefficient. The other conclusions are the same as those presented in the previously cited publications. Similar conclusions concerning the influence of the friction coefficient between the material and the tool were shown in the article [17]; however, the authors note that the impact is small.

A similar although separate issue is an analysis of the multilayer sheets bending process. Such laminates are gaining in importance due to their wide applications in automotive industry. The article [10] presents an analysis of the impact of the individual layers thickness of the Al3105-PP-Al3105 composite (aluminum alloy - polypropylene - aluminum alloy) and it demonstrates that the springback coefficient has a different value depending on the thickness of individual layers regardless of the total thickness of the sheet constant.

The literature survey demonstrated that there is no sufficient information about the numerical simulations of the coated sheets bending process. The use of numerical methods could significantly improve the process preparation from the technological side and this could lead to the preparation time and cost reduction. It is vital to develop an accurate model of the coated sheets bending process which could result in an industrial productivity increase.

## 2. RESEARCH METHODOLOGY

The subject of the analysis is the bending process of DC01 steel with a high-thickness zinc coating. The model was prepared using the Solidworks software, while the calculations were made using the Ansys Workbench environment. A detailed process of the model preparation and simulation is presented in the subsequent sections.

### 2.1. Model geometry

The process diagram with the tools' dimensions is shown in Figure 2.

The calculations were made for a $d$ = 1 mm thick DC01 steel sheet which was 10 mm wide. A double-sided zinc coating was applied, with a thickness of: 0.1; 0.15 and 0.2 mm. The radius of the punch and the die bottom was $R$ = $r$ = 5 mm; the angle between the working surfaces of both the punch and the die was 60°. The die width was 25.4 mm.

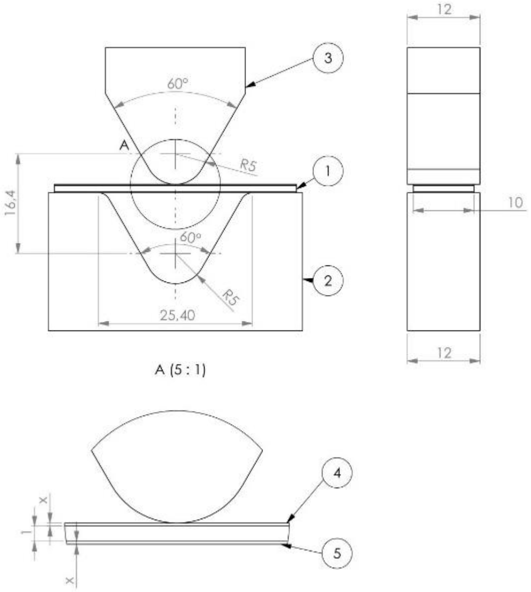

Fig. 2. Model geometry. 1 – steel sheet, 2 – die, 3 – punch, 4, 5 – zinc coating, $x$ – coating thickness

### 2.2. Material model

The materials used in the analysis included DIN EN 10130 DC01 steel and metallic zinc. In both cases, the material model assumed the use of the Isotropic Elasticity model as well as the Bilinear Isotropic Hardening model. The strength parameters of the materials simulated are presented in Table 1.

Due to the fact that the tools were not the subject of the analysis, the structural steel from the Ansys material library was selected. There were only elastic models applied with the Young's modulus of 211 GPa and the Poisson's ratio of 0.3. The hardening model was not used for this material.

### 2.3. Model preparation process

The first step was a manual definition of contacts between model elements. Two types of contact pairs were used. A frictional contact with a friction coefficient of 0.1 was used between the punch and the coating layer and between the coating and the die (Fig. 3). The contact between the steel sheet and the coating layers was set to the bonded type.

Tab. 1. Strength parameters of materials used in the simulation

| Parameter | Material | |
|---|---|---|
| | DIN EN 10130 DC01 [15] | Zn [14] |
| Young's modulus, GPa | 200 | 90 |
| Poisson's ratio | 0.29 | 0.25 |
| Yield strength, MPa | 280 | 75 |
| Tangent modulus, GPa | 1 | 0.45 |

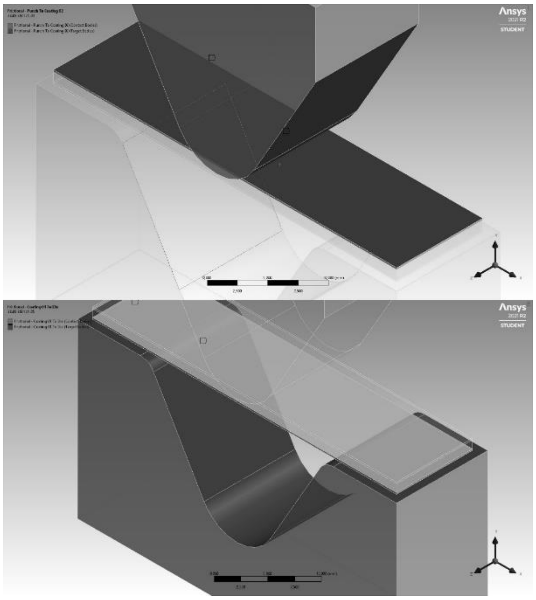

Fig. 3. Contact pairs punch – coating (top) and coating – die (bottom)

The next step was a discretization of the model using a finite element mesh. As the parts which were not covered by the analysis, the punch and die geometry were divided into finite elements with a maximum size of 4 mm. The working surfaces of the tools were divided into finite elements with a maximum size of 1 mm using the Face sizing command. Using the Body sizing command, the maximum size of the finite element used for sheet discretization was set to 1 mm. Similarly, the maximum size of the finite element of the coating layer is 0.25 mm. Using the Patch Conforming Method command, the preferred shape of the finite element within the steel sheet was selected as a tetrahedron. The finished mesh of finite elements is shown in Figure 4.

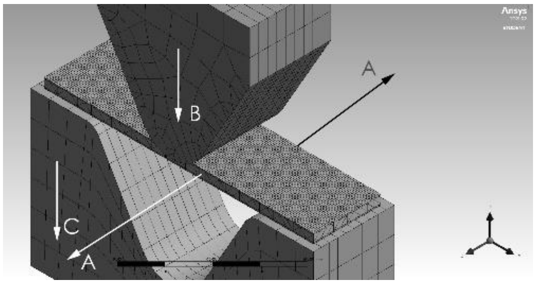

Fig. 4. Finite elements mesh used in the analysis and boundary conditions: A – plate displacement in Z axis (0 in each time step), B – punch displacement in Y axis (see the Fig. 5), C – die displacement in Y axis

Next, the simulation parameters and the boundary conditions were defined. The simulation was performed in ten steps, each of which lasted 1 s. In order to stabilize the position of the sheet bent, its displacement in relation to the Z axis was blocked by setting the displacement to 0 in each of the time steps. Both the punch and the die moved along the Y axis according to the declared value in each of the time steps. Three cases of stamp displacement were considered: 13.5 mm; 10.125 mm and 6.75 mm respectively. The displacement of the stamp in successive time steps is shown in Figure 5.

In each case, the die was stationary until the time step *t* = 8 s, then it moved down by a given value in order to move away from the bent sheet. This procedure was applied to eliminate any potential influence of the die on the springback phenomenon.

The last step was to solve the model for each of the punch displacements (13.5 mm; 10.125 mm and 6.75 mm) and each shell thickness (0.1 mm, 0.15 mm and 0.2 mm), which resulted in nine separate cases.

## 3. RESULTS AND DISCUSSION

### 3.1. Maximum equivalent plastic strain analysis

Using the Ansys software capabilities, the maximum value of equivalent plastic strain at particular moments of time was recorded. The results collected are presented in the subsequent charts. Figure 6 shows the maximum plastic strain as a function of time for a punch travel of 13.5 mm. Similarly, Figure 7 shows the data for a travel of 10.125 mm, and Figure 8 for 6.75 mm.

In each case, the highest value of plastic strain was recorded for the sheet with the highest coating thickness. A significant difference between the course of the maximum plastic strain can be observed in the case of the punch travel of 13.5 mm and the cases of 10.125 mm and 6.75 mm. It can be noticed in the period between *t* = 3 s to *t* = 6 s. This is due to the fact that in the 13.25 case, the punch presses the sheet bent against the die walls, while in other cases the sheet is supported only at three points (on the edges of the die and the punch). This situation is illustrated in Figure 9.

It was also observed that the plastic strain in the tensile zone was each time greater than that in the compression zone, which confirmed the observations made in [4]. An example of the plastic strains distribution is shown in Figure 10.

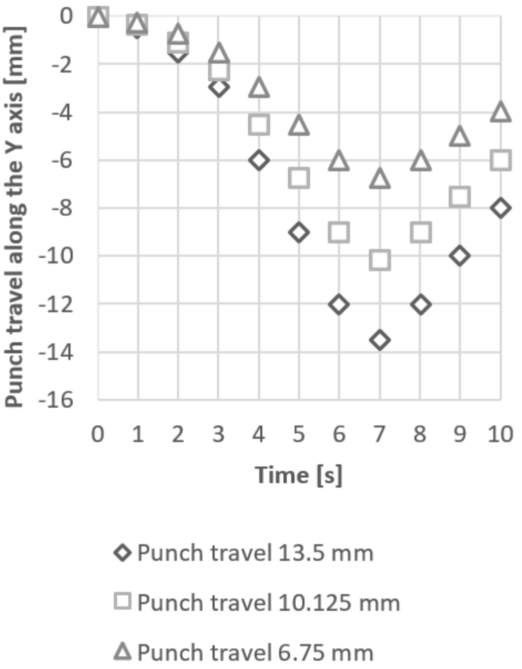

Fig. 5. Punch travel along the Y axis in individual time steps for each case

### 3.2. Reaction force along the Y axis analysis

The reaction force value which acted on the punch along the Y axis for individual punch travels is shown in the diagrams (Figures 11, 12 and 13).

In each case, a significant increase in the reaction force can be noticed at the time *t* = 0.2 s, this is the force necessary to induce plasticizing stresses. After the material enters the state of plastic deformation, the reaction force decreases, but this shows an incremental nature, up to the time *t* = 6 s, where there is a noticeable decrease in the reaction force and its re-increase until the end of the bending process (*t* = 7 s).

In each case, bending the sheet with a greater coating thickness required a greater load, which could be justified by an increase in the total sheet thickness.

### 3.3. Springback analysis

Using the deformed geometry measurements in the Ansys software, the sheet bending angle was determined at the moment of the maximum punch travel (*t* = 7 s) and after complete unloading (*t* = 10 s). Then, basing on the equation (1), the springback coefficient K was calculated. The results of the calculations are presented in Table 2.

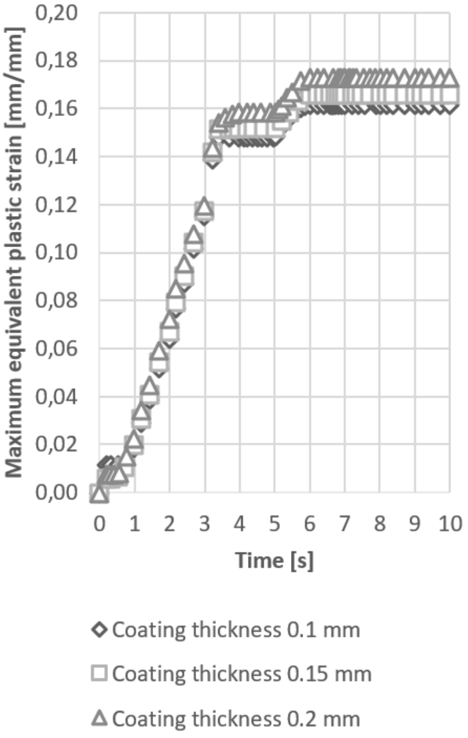

Fig. 6. Maximum equivalent plastic strain as a function of time for the punch travel of 13.5 mm

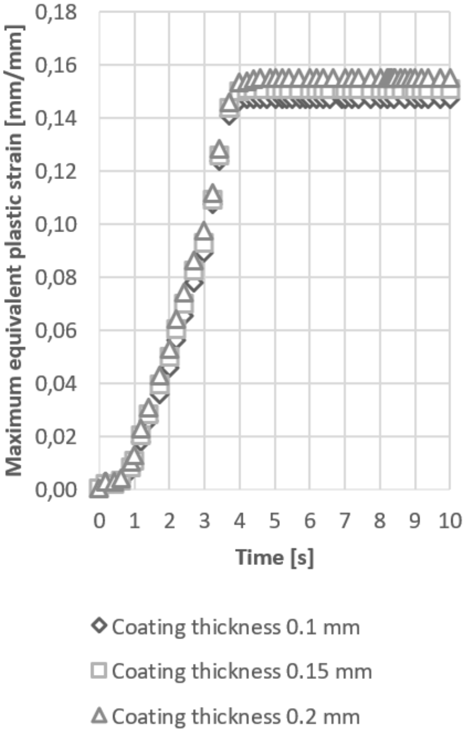

Fig. 7. Maximum equivalent plastic strain as a function of time for the punch travel of 10.125 mm

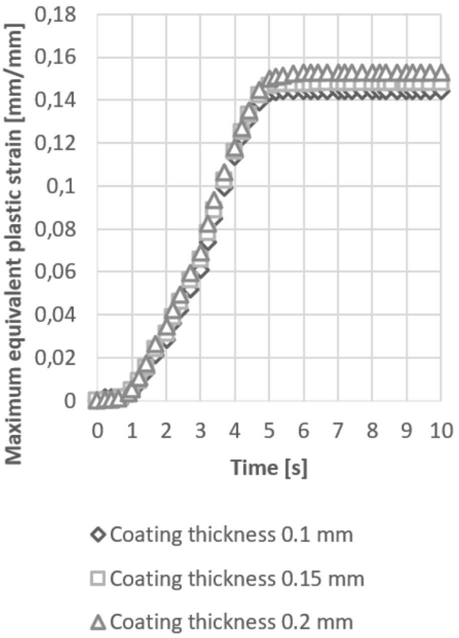

Fig. 8. Maximum equivalent plastic strain as a function of time for the punch travel of 6.75 mm

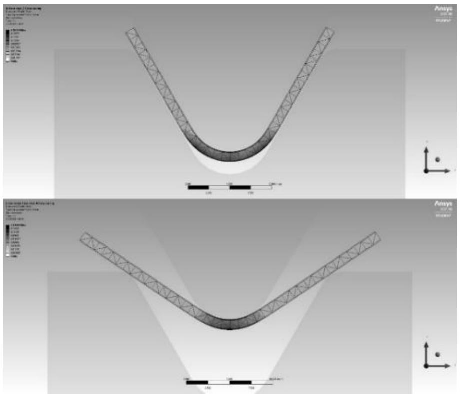

Fig. 9. Sheet position in the case of maximum punch travel of 13.5 mm (top) and 6.75 mm (bottom)

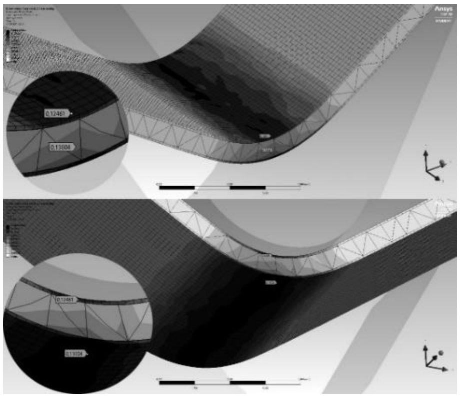

Fig. 10. Distribution of plastic strains for 0.1 mm coating and punch travel of 6.75 mm. Compression zone – top, tensile zone - bottom

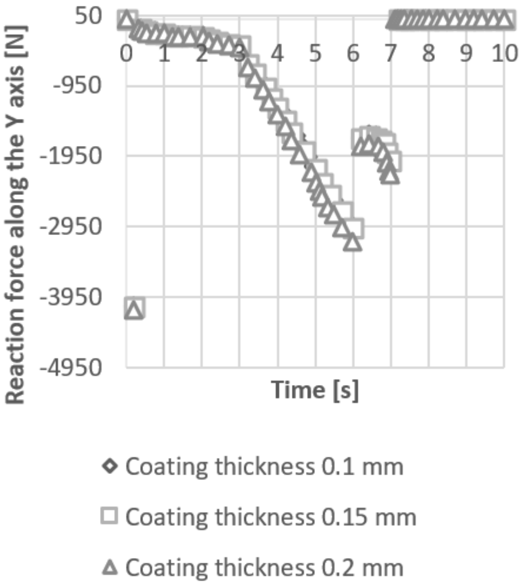

Fig. 11. Reaction force along Y axis with punch travel of 13.5 mm

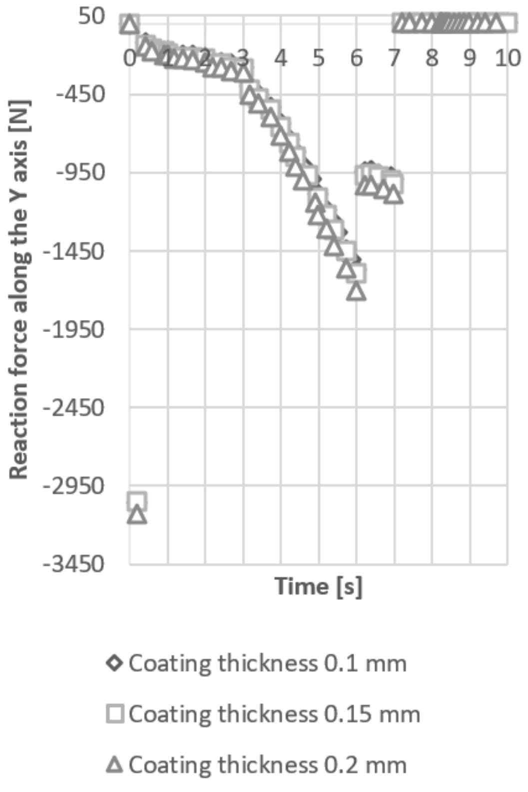

Fig. 12. Reaction force along Y axis with punch travel of 10.125 mm

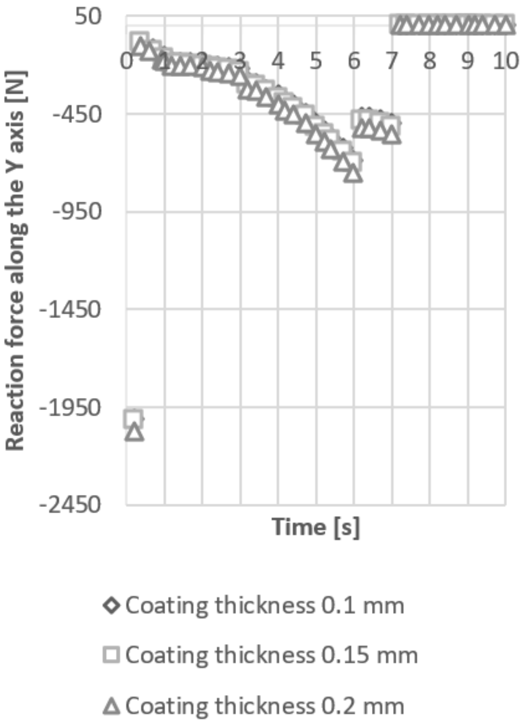

Fig. 13. Reaction force along Y axis with punch travel of 6.75 mm

Tab. 2. Strength parameters of materials used in the simulation

| | K coefficient value | | |
|---|---|---|---|
| Coating thickness | Punch travel 13.5 mm | Punch travel 10.125 mm | Punch travel 6.75 mm |
| 0.1 | 1.035 | 1.043 | 1.042 |
| 0.15 | 1.037 | 1.042 | 1.034 |
| 0.2 | 1.064 | 1.040 | 1.031 |

In the case of punch displacement over the full distance of 13.5 mm, it was noticed that a greater thickness of the coating increased the springback coefficient, which is consistent with the observations made by the authors of the publications [7], [8] and [12]. However, in the case of smaller punch displacements, where the material was not pressed against the entire surface of the die, the opposite situation was observed. A possible explanation is a much greater thickness of the coating than in the research conducted by the above-mentioned authors, so that an increase in the sheet thickness had a greater impact on the springback coefficient, which is consistent with studies [1, 4, 6, 13]. However, this issue needs to be clarified through further research.

## 4. CONCLUSIONS

The simulations conducted allowed an evaluation of the phenomena occurring during the bending of steel sheets coated with a thick layer of zinc coating. The analysis of the data collected allowed the following conclusions:

1. An increase of the coating thickness leads to an increase in the magnitude of the maximum plastic strain. This can be explained by the fact that the sheet thickness increasement caused by the application of the coating moves its surface away from the neutral zone. Thus, there is an occurrence of higher deformation values.
2. According to the observations made by other authors [4], plastic strains reach a higher value in the tensile zone (i.e. the die side). This is because the sheet is wrapped around the punch radius. The bending radius on the punch side is equal to its radius, while the outer radius is magnified by the sheet thickness.
3. The reaction force acting on the punch as a function of time is similar in each case; however, increasing the punch travel and thus the bending angle requires the use of a greater force.
4. A thicker coating increases the force required to carry out the process regardless of the bending angle. This can be explained by increasing the total sheet thickness.
5. In the case of a 13.5 mm punch displacement, where the sheet was pressed against the working surfaces of the die, an increase in the springback coefficient was observed along with an increase in the thickness of the coating, which is in line with the observations made by other authors [7, 8, 12].
6. In the case of three point bending (punch travel 10.125 mm and 6.75 mm), it was noticed that the springback coefficient decreased with increasing the coating thickness, which is in contrast to the findings of the afore-mentioned studies. However, a much greater thickness of the coating should be noted in the studies of the authors of this paper. The discrepancy in the observations can be explained by a significant increase in the sheet thickness, which has the effect of reducing the springback coefficient according to publications [1, 4, 6, 13].

The results obtained could be implemented in the industrial practice to aid the coated sheet bending process design and especially in terms of the springback phenomenon prediction, as it was demonstrated that it is affected by the coating application as well as the coating thickness. It is clear that coated sheets are commonly used in the industry because of their high corrosion resistance compared to their cost, so it can be stated that the issues covered in this article are important and up to date for the current industry market situation.

Those results could also be significant in the scientific area as the coated sheets bending process has not so far been an object of numerical simulation, so the results achieved could be used to prepare more detailed and thorough simulations, which could lead to the understanding of the complex phenomena which occur in the bending zone.

In conclusion, it needs to be stated that this numerical simulation is on its early stage of development. It proved to be useful in predicting the springback factor as well as the punch reaction force and plastic strains in the bending zone, which could be helpful in the coated sheets bending process design even though it has some limitations at this early stage. There was an isotropic material model used, and the sheet anisotropy is an important factor affecting the springback coefficient and a proper selection of bending process parameters. This model also neglects the coating adhesion loss possibility, which may occur especially during bending with the radius close or equal to the sheet thickness, where equivalent plastic strains possess the greatest value.

An investigation into the influence of the parameters such as the bending radius and a coating thickness lower than 0.1 mm should be also conducted.

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## Biographical notes

**Mateusz Miksza** received his M.Sc. degree in Mechanics and Machine Design in Machinery Construction and Operation from the Koszalin University of Technology in 2015. As a graduate, he was employed as a mechanical designer in the field of automotive industry. He started his Ph.D studies in the Doctoral School of the Koszalin University of Technology in 2020. His scientific interests focus on sheet metal bending and metallic materials fatigue life issues. He has published six scientific papers in national journals and book chapters.

**Łukasz Bohdal,** starting from 2009, a researcher and a lecturer at the Koszalin University of Technology, currently employed as a university professor. He conducts basic and applied research in cooperation with business entities. His main specialties include mechanics, designing innovative structures and technologies, modeling, optimization. An author over 100 scientific publications and one monograph. He completed 4 internships of a research or didactic nature. He has carried out 27 research works of an industrial, implementation and development nature. He has participated in consortia and research networks. A co-author of 2 foreign patents. He has participated in the implementation of 12 projects as a manager or main contractor.

**Katarzyna Kośka** received her M.Sc. degree in Mechanics and Machine Design in Machinery Construction and Operation from the Koszalin University of Technology in 2020. Then she started her Ph.D studies in the Doctoral School of the Koszalin University of Technology. Her scientific interests focus on the tool wear in the metallic materials punching process and its influence on the process quality and efficiency. She has published seven scientific papers in book chapters.